2.1.2 Introduction

Mechanical weed control has been a sustainable option for weed removal throughout farming history. However, controlling weeds with mechanical means is challenging and requires the combination of different weeding techniques and cultivation strategies to achieve economically acceptable weed control levels (Oriade and Forcella, 1999). Additional challenges include the high weather dependency and the slow working speed of mechanical weed control operations compared to a conventional sprayer. The scientific literature reports on various positive and negative results of studies dealing with mechanical weed control. Wiltshire, Tillett and Hague (2003) and Kunz, Weber and Gerhards (2015) found that mechanical weeding alone or in combination with herbicides produced similar sugar beet yields as conventional spraying. Rasmussen (2004) also achieved positive yield results in cereals for mechanical weed control whereas (Lötjönen and Mikkola, 2000) observed that mechanical weeding could also reduce grain yield or show no effect at all.

Despite its complexity, mechanical weeding should be viewed as a valuable complement to chemical weed control. Today, the main drivers for the introduction of mechanical weed control include the global spread of herbicide-resistant weeds and also the lack of herbicides for various crops (Busi *et al*., 2013). Herbicides became a limited resource because only a few herbicides with a new mode of action were discovered during the past 20 years (Duke, 2012). With currently 262 (152 dicotyledon and 110 monocotyledon) herbicide-resistant weed species globally (Heap, 2020), alternative weed control methods and effective resistance management practices, as required for Integrated Pest Management (IPM), are essential to further decrease herbicide usage (Harker and O'Donovan, 2013). Furthermore, political trends must be kept in mind. The new EU restrictive legislation laid the groundwork for the aim of reducing agricultural pesticide use by 50% in Europe by the year 2030. Until then it is important to find suitable alternatives that can compensate the loss of synthetic herbicides. Finding suitable alternatives for fungicides and insecticides is also of great importance, however, this is not the focus of this work.

In contrast to spraying, mechanical weeding involves the repetitive, direct physical contact of tools with the soil. There is no straight answer to the question of how many passes are necessary with a mechanical implement to maximize weed control whilst minimizing crop damage. The treatment amount (frequency) and intensity depend on several factors including the crop growth stage, weed growth stage, weed density, row spacing and the soil conditions (Melander, Rasmussen and Bàrberi, 2005; Van Der Weide *et al*., 2008; Kolb and Gallandt, 2012). However, some general assumptions can be made about different crops. For example, sugar beets, soybean and maize have a wide row spacing and usually require between 2 and 3 mechanical treatments (Gunsolus, 1990; Kunz *et al*., 2018). In competitive crops like cereals, where the row spacings are usually small, 1–2 passes with the harrow can suffice to achieve a sufficient weed control efficacy (Brandsæter *et al*., 2012). Mechanical weeding always poses the risk of partial crop damage or even complete crop plant loss. Physical damage to crop plants may stunt plant growth and allows pathogens to enter which may lead to secondary infections and also decreases the yield (Findlay *et al*., 1996). For example, sugar beet roots can be infected with Fusarium- or Phoma root rot if they suffer mechanical damage (Draycott, 2008, p. 304). Due to the risk of imminent crop damage, exact guidance of the mechanical tools is essential.

But despite all modern sensor technology, the basic concepts of mechanical weeding must be kept in mind to identify the parameters that can be improved for a higher weed control efficacy and ease of use for the operator. Factors that need to be considered for effective mechanical weed control are the treatment timing, frequency, cultivator type and intensity (aggressiveness). The crop growth stage, soil texture and moisture as well as the preceding and subsequent weather conditions must also be taken into account. Especially the timing of treatment is an often-discussed topic among farmers but general assumptions about the timing and frequency of a mechanical weeding operation are difficult to make since this is highly location specific (Oriade and Forcella, 1999). Farmers generally agree that the earlier mechanical treatments are applied, the greater is the weed control effect and the resulting yield. Several studies support the importance of early weed control in different cropping scenarios including dry beans (Vangessel *et al*., 1998), onions (Bond *et al*., 1998) and winter wheat (Welsh *et al*., 1999; Knezevic *et al*., 2002; Melander *et al*., 2003). Knezevic *et al*. (2002) also highlight this issue by providing a general concept on the critical period for weed control. However, a study by Rasmussen *et al*. (2010) conducted in spring barley indicated that different treatment timings within a 2 week window did not affect crop yield and it was concluded that adjusting the harrowing intensity to the crop growth stage was more important than the timing of post-emergence harrowing. All studies share the view that the type of cultivation measure has a great influence on the weed control efficacy.

The three cultivation categories for post-emergent mechanical weed control in agricultural row crops are:

1) **whole field treatments,**
2) **inter-row, and**
3) **intrarow treatments.**

Whole field treatments refer to methods which treat the entire field, whereas inter-row and intrarow mechanical weeding leaves the close- to-crop area untreated. Harrowing (Figure 2.1.2-1) or rotary hoeing are typical implements for whole field treatments, where damage to a certain percentage of crop plants is expected and tolerated. Harrowing is suitable for various crops including cereals, maize, peas, and soybean. Some crops (e. g. sugar beets) are less suited for harrowing due to their delicate leaves and may suffer yield losses (Ascard and Bellinder, 1996). In general, harrowing in sugar beets is possible but it requires an in- creased seed density and it should not be performed before the true 4 to 6-leaf stage of the beets (De Buck *et al*., 1999; Van Der Weide *et al*., 2008; Cioni and Maines, 2010). Therefore, it can be used in addition to hoeing but since sugar beets need intensive weeding even prior to the 4-leaf stage, a reliance on harrowing alone could be inadequate for effective weed control. Inter-row treatments (e.g. hoeing) cultivate the space between the crop rows (Figure 2.1.2-1) and intrarow weeding refers to treatments of the crop row. Usually a combination of inter-row and intrarow treatments is applied simultaneously to maximize the treated field area. A typical set up for maize or soybean would be a hoe with goosefoot

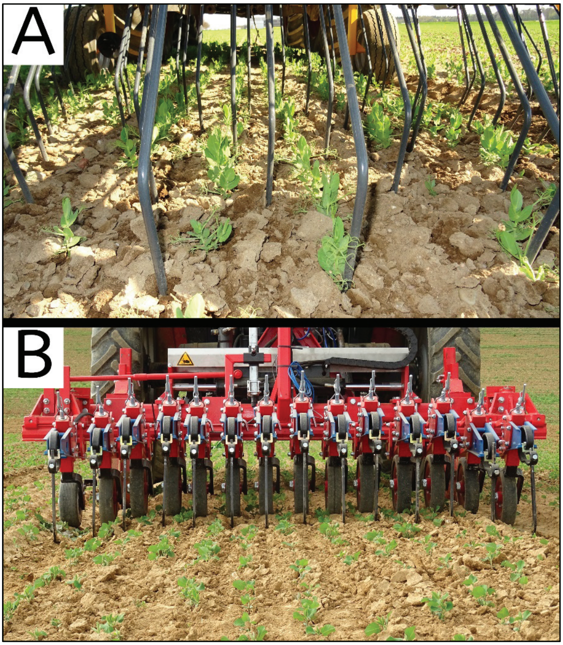

Figure 2.1.2-1: Harrowing peas (A) and hoeing in soybean (B).

sweeps in combination with finger weeders. Finger and torsion weeders are specialized tools which are very effective at removing weeds from the crop row (Riemens *et al*., 2007; Van Der Weide *et al*., 2008).

Keeping this in mind, it is clear that sensor-based (intelligent) cultivators must be able to either identify crop row structures or single crop plants, to ensure an optimal alignment of the tools with the crop. The mechanical tools should be guided as close to the crop plants as possible to increase the treated field area. However, physical crop damage must be avoided. Crop plants are easily damaged due to steering or guidance errors, which can lead to considerable yield losses (Home *et al*., 2002; Melander, Rasmussen and Bàrberi, 2006). This stresses the importance of accurate cultivator guidance. The closer the weeding implements are guided along the plant rows, the more important precise steering becomes (Melander and Hartvig, 1997).

Research information and the resulting conclusions must be transferred into production systems. Therefore, Table 2.1.2-1 summarizes 9 basic requirements that must be fulfilled for half or fully automated weeding systems to be robust and efficient in typical farming environments. After all, higher digitization also corresponds with higher acquisition costs and utilizing modern technology must combine certain new advantages to be ecologically and economically profitable.

Table 2.1.2-1: Basic requirements for efficient sensor-guided mechanical weeding machines.

- Avoidance of crop plant damage by increasing the precision of the implement guidance and correctly identifying crop rows or single crop plants in different growth stages
- Cope with varying field characteristics such as terrain slopes, different soil types, high weed pressure, crop row gaps (missing crop plants), and varying crop appearance (e.g. crop height and red vs. green plants)
- Economic advantages must be present to compensate for higher acquisition costs
- Enable less experienced operators to perform advanced weed control tasks (e.g. hoeing close to a crop row)
- Ensure a consistent working depth of the tools in the soil
- Extend operation time from daylight to nighttime
- Facilitate the workload by automatically guiding the implement(s)
- Increase ground coverage by enabling higher driving speeds
- Robustness of all system components to withstand varying field, weather and illumination conditions including dust, water, temperature variations, machine vibrations, lateral and horizontal forces that may arise during the application of treatments

This study focuses on smart technologies where sensors are used for the detection of weed or crop structures to perform mechanical weeding. Where possible, experiments that provide solid facts on the performance of specific methods and technologies are included. The discussion pinpoints challenges of current and future mechanical weed control technologies. This review has been divided into four sections to gain a better overview of the relevant possibilities for sensor-guided mechanical weed control. The sections are (I) Autonomous Robots and (II) Half Autonomous Tractor-pulled Implements which are divided into (IIa) Machine Vision, (IIb) GNSS Sensor Systems and (IIc) Laser and Ultrasonic Sensors.

2.1.3 Autonomous Robots

Agricultural robots can be used for many different field applications including harvesting or weed control. Their appearance and set up may vary and can range from a modified tractor to a small, specialized platform which travels the field autonomously to execute a crop operation (Emmi *et al*., 2014). Robotic systems have been an essential part of industrial style work lines for many years (Day, 2011). But their implementation in food and farming systems has been troublesome because of the complex, unstructured and everchanging environments as illustrated in Table 2.1.3-1 (Nof, 2009; Day, 2011; Hiremath *et al*., 2013; Bechar and Vigneault, 2017; van Henten *et al*., 2017).

Table 2.1.3-1: Robots in agriculture and other environments, adapted and modified from Bechar and Vigneault (2017).

	Environment	
	Structured	Unstructured
Structured objects	Industrial domain	Military, space, underwater, mining domains
Unstructured objects	Medical domain	Agricultural domain

Even though agricultural robots do not have to be as accurate as industrial robots on a cm vs. mm scale, they must cover large areas and are often faced with deviating terrain slopes and irregular field sizes (Edan, 1995). Furthermore, the exact location of and the distinction between weed and crop plants is a crucial prerequisite for robotic systems to perform mechanical weeding (Baerveldt and Åstrand, 2002). This task is hindered by variations in plant appearance, alternating weed pressures and weed populations from field to field during the entire cropping season and must be tackled with highly developed software solutions (Midtiby *et al*., 2016). The complexity of creating robots for agricultural applications was well addressed by Bechar and Vigneault (2017): in contrast to industrial uses, agriculture is the only domain where unstructured objects coincide with an unstructured environment. Therefore, creating autonomous mobile robotic systems for agricultural applications first became a realistic aspect of scientific studies with the advancements made in sensor-supported field machinery in recent years (Ruckelshausen *et al*., 2006).

Concerning weed removal with autonomous mobile robots, Slaughter *et al*. (2008) specified the following technical requirements as the essential characteristics: self-guidance, weed detection, and identification, precision intrarow weed control, and weed mapping. Of those characteristics, plant detection, identification and determination of the exact position are the most challenging tasks. To locate crop or weed plants, a series of steps are necessary and there are two main concepts of using robotic systems for plant care and mechanical weeding. The first one is geo-referencing the planted or seeded crop plants via GNSS (Global Navigation Satellite System) and storing their exact location in a plant map (Pérez-Ruiz and Upadhyaya, 2012). A robotic system can later use this information to locate each crop plant and perform the necessary weeding tasks. However, the disadvantages are that errors during seeding or planting are going to affect the performance of the weeding process. If weeding is solely based on GNSS information, irregularly spaced crop plants are not considered and will be damaged or killed. Planting can be an option to avoid dislocation of the seeds during seeding, but it is not always possible or economically feasible. Studies concerned with the creation of seed maps showed that the location of mapped crop seeds can be within 34 mm (Ehsani *et al*., 2004) or 16–43 mm (Griepentrog *et al*., 2005a) of the germinated crop plants. These results indicate that creating seed maps can be feasible for accurate weeding operations. Still, a more advanced concept is seen in the combination of machine vision and GNSS-navigation. The robotic system receives the necessary GNSS coordinates for general field navigation, but it must be able to detect crop plants or rows on its own without a-priori-knowledge in terms of a seed map. Camera-guided implements can then perform mechanical weeding on the exact location of the crop plants or along crop rows.

Studies of using GNSS-referenced crop plants for mechanical weed control can be found in Nørremark *et al*. (2008, 2012). Their robotic system was able to perform mechanical inter- and intrarow weed control while traveling along crop rows with a cycloid hoe. It was found that in combination with the intrarow treatment of the cycloid hoe, up to 91% of the field area could be treated. This represents a large amount of field area which in turn could result in a high weed control efficacy. Similarly, Bakker *et al*. (2010c), Bakker *et al*. (2010a), Bakker *et al*. (2010b) described the application of an Intelligent Autonomous Weeder (IAW, Wageningen University) for inter-row hoeing in maize with RTK- GPS (Real Time Kinematics Global Positioning System) referenced seeding. The authors state that no crop plants were damaged at a driving speed of 0.5 m s^{-1}. Both studies demonstrated that autonomous mechanical weeding is possible with GNSS-derived data. However, the mean working speed of 0.5 m s^{-1} is not as fast as a conventional tractor would work. The slow working speed could be compensated by the robotic system working day and night. However, another problem arises: usually, much higher driving speeds of at least 4 km h^{-1} are needed for effective mechanical weed control with conventional tractor-pulled implements for mechanical weeding. Some implements such as harrows even require driving speeds of at least 6 to 12 km h^{-1} to provide the best weed control efficacy (Bowman and Outreach, 2002). The reason is that large proportions of weed plants are not only cut or uprooted by hoeing devices, but also a certain amount of small weed plants are buried with soil, and their growth is impeded. This implies that effective weeding implements for robotic systems should be of a rotating or similar actively engaging nature because robotic systems cannot generate high enough speeds for the soil burial effect to happen due to their comparatively slow working speed. Especially rotating tools are very powerful, and they even kill large weed plants which hoes, or harrows may not be able to eliminate. Thus, rotating implements are the ideal solution to compensate for the speed limitations that robotic systems have.

The BoniRob platform by Bosch Deepfield Robotics has such an active tool to perform mechanical weed control (Langsenkamp *et al*., 2014). A stamp is positioned above a weed plant and is then lowered onto the plant to destroy it. This might work in light soils, but difficult soil conditions and the slow working concept will be problematic. The tube-stamp is therefore not seen as a promising method for mechanical intrarow and close-to-crop weed control despite its weed control efficacy of up to 94%. Nørremark *et al*. (2012, 2008) addressed the issue of finding a suitable tool for mechanical weeding with robots by developing and testing a cycloid hoe for intrarow treatments. However, limiting their navigation ability to GNSS derived data and excluding additional features, such as machine vision, does not entirely satisfy the requirements of an autonomous field unit.

Instead of using GNSS-reference data, Baerveldt and Åstrand (2002) equipped a robotic system with a forward-looking camera working with a grey level vision system and a near-infrared filter. The system was able to locate sugar beet rows and identify single sugar beet plants. After identifying the position of each sugar beet plant, a mechanical tool consisting of a rotating wheel was lowered by a pneumatic cylinder. The wheel rotated perpendicular to the crop row, thus eliminating weeds around each sugar beet. This setup demonstrated how robotic systems can cater to single crop plants. Further improvements should provide the robot with the ability to access a nearby charging station on its own if power levels reach a critically low level.

Apart from weed control in a field, robots may also be used in pastures to eliminate certain weed species, thereby decreasing the required manual labor (van Evert *et al*., 2011). An autonomous robot was developed and tested by van Evert *et al*. (2011) to find and eradicate broad-leaved dock (*Rumex obtusifolius* L.) on a commercial farm. Navigation was achieved with a predefined path on which the robot navigated via GNSS. A downward-looking camera then identified *R. obtusifolius* plants and a mechanical tool was positioned over the center of the weed plant. The tool was lowered onto the plant and rotating knives cut the plant to pieces. Van Evert *et al*. (2011) reported a successful weed detection rate of 93% and the successful removal of 75% of those plants. Large weeds, such as *Cirsium arvense* L. or *Rumex* spp. L. are often a problem in pastures. Manual labor is required to remove those plants by hand or by spraying them with an herbicide. Being able to rely on automatic mechanical weeding systems for removal of such weed species would be of great environmental importance and it would drastically decrease manual working hours. By using more than one autonomous system per field the working time could be decreased further. Thereby the treated pasture area would increase immensely.

Based on this idea, Noguchi *et al*. (2004) devised the concept of a fleet of robots according to a master–slave system. In such a system several autonomous vehicles execute all agricultural work related to the crop from sowing until harvest. A master-robot incorporates the function of decision making and planning, while one or more slave-robots follows the master-robot and assist in the assigned tasks. The RHEA Project (Robotics and associated High-technologies and Equipment for Agriculture) took small market available tractors and modified them to perform agricultural tasks on their own. Supervision is provided by a multi-level architecture with several supervision levels. The tractors were equipped with machine vision for weed and crop row detection, laser range finders for obstacle detection and GNSS for general navigation in the test field (Emmi *et al*., 2014). Pérez-Ruiz *et al*. (2015) equipped one of the RHEA project tractors with a mechanical-thermal weeding tool. While the thermal tool was machine vision assisted and selectively eliminated intrarow weeds in maize, the mechanical tools performed continuous inter-row hoeing regardless of weed cover. A detailed description and images of the mechanical implements can be found in Gonzalez-de-Santos *et al*. (2017). The mechanical-thermal combination achieved weed reduction results of 90% and no major crop losses were recorded. Besides maize, the RHEA-fleet-system has been tested in other crops such as onion and garlic (Conesa-Muñoz *et al*., 2015). At Harper Adams University the “hands-free hectare project” (Hands free hectare, 2018) followed the same concept. In 2017 it was the first project to fully automate a single crop cycle in spring barley from sowing until harvest. No mechanical weed control was performed, but more results can be expected in the future.

The AgBotII (Bawden *et al*., 2017) has been developed as another agricultural robot combining mechanical and chemical weed control implements. Individual weeds were classified and either removed mechanically or treated with a chemical compound. Classification accuracies of 90% were achieved. According to the authors, weed removal with the mechanical tools was successful in removing wild oats and sowthistle. By combining mechanical and chemical weed control strategies robots may become a powerful alternative to conventional control techniques.

Eventually, such systems may be used in everyday farming situations. However, until then major work is required. The biggest problem is to guarantee a continuous operating state of the robot. Therefore, robotic manufacturers should focus on providing adequate customer support in case of a malfunction. The support should consist of online solutions as well as local technicians who could quickly act and perform necessary on-farm repairs. Today even tractors are equipped with high-end technology and often the farmer is no longer able to perform necessary repairs. During critical time periods (e.g. weeding, harvesting) the farmers need the maximum machine uptime and availability of the relevant equipment. Possible failures need to be fixed as soon as possible, which can be hindered by the lack of available personnel and know-how. The maintenance of robotic units will not be any less easy. However, despite the obstacles robots have to overcome in an agricultural environment, their potential is being increasingly developed and can help to reduce environmental costs in conventional precision farming, and the required human labor in organic farming (Gobor, 2013; Chen *et al*., 2016). Since robots are usually small vehicles, they can easily be powered with solar panels and electricity which eliminates the dependency on fossil fuels. Furthermore, robots can work 24 h a day and are able to replace human labor even if they are slower working than a skilled worker.

Several companies are working on autonomous solutions for mechanical weeding to keep the input of herbicides on the environment as low as possible. NAÏO (France) provides three models of robots ("OZ", "DINO" and "TED") for agricultural tasks, which can partially work autonomously (Autonomous weeding, agricultural robots - Naïo Technologies, 2019). However, navigation of their robots is mostly based on RTK-GPS navigation with a pre-planned path and still requires an elaborate setup. Similar to NAÏOs "DINO" robot model, the company Carré (France) is working on a related concept with the development of the "ANATIS" robot. It is also supposed to aid farmers in vegetable farming by performing mechanical weeding (Carré - Made for Agriculture, 2020). Also, small systems like the "Tertill" are developed for small scale weeding in gardens (Franklin Robotics | Home of Tertill, the robotic garden weeder that is powered by the sun!, 2020). Even though a small robot can only tend to a limited area they could also be used in a swarm of many robots to treat entire fields. An advantage would be that single units can be replaced quickly. Other robotic systems, which are still under development and not yet commercially available exist. This includes the PUMAgri by SITIA which is also being developed with the aim to reduce the herbicide input in agriculture (Platform PUMAgri - Sitia - Bancs d'Essais et Innovation Robotique, 2020).

From the previously mentioned robotic systems the sizes can vary between very small units (TerTill or OZ) to robots the size of a small tractor as in the RHEA Project. Much larger robots are not seen as an advantage because soil compaction would increase dramatically. The idea behind robot systems is that they should perform repetitive tasks 24/7 to maintain a low weed pressure. Therefore, agricultural robots must not be too heavy. Otherwise the negative effects due to soil compaction would outweigh the benefits of the mechanical weed control measures. Apart from the size and weight of an intelligent implement for weeding, sloping terrain is also an issue as mentioned in Table 2.1.2-1. The company Energreen explicitly created the RoboZERO robot for weeding and mowing which can cope with slopes of up to 30° (Robozero Weeding Robot, 2020). However, it is controlled via a remote control by an operator and does not fully work autonomously. A system which combines all the prerequisites for successful sensor guided mechanical weeding is the robot produced by FarmWise. Based on deep learning, their robot captures and analyzes plant images to detect and remove weeds (FarmWise, 2020). It seems to be a very robust system that can be used for long-term field work in many conditions. A similar but solar powered autonomous robot is the "Farmdroid FD20" which can perform sowing and hoeing between crop rows. By combining sowing and weed control, an interesting hybrid robot has been created which can contribute to the general concept of autonomous farming. According to their website, the Farmdroid can care for 20 ha per season

(FarmDroid FD20, 2020). It is a slow working robot (1 km h^{-1}) but this can be compensated because it works continuously.

2.1.4 Half Autonomous Tractor-pulled Implements

2.1.4.1 IIa Machine Vision Systems

The benefits of machine vision for industrial uses also led to in- creased research in a variety of agricultural applications such as crop row following (Åstrand and Baerveldt, 2005) and automatic guidance of robotic systems (Baerveldt and Åstrand, 2002; Pérez-Ruiz *et al.*, 2015; Gonzalez-de-Santos *et al.*, 2017). However, the following factors can negatively impact image acquisition and processing in the field: (1) Changing environmental conditions, (2) varying plant sizes and shapes, (3) missing crop plants in a row (Åstrand and Baerveldt, 2005), (4) contamination of plants by foreign particles and thereby changing their appearance (Montalvo *et al.*, 2013) and (5) diverging amounts of weeds present in the field (Slaughter *et al.*, 2008).

Unfavorable conditions for image acquisition and the ideal placement of the camera in relation to the mechanical weeding implement were issues that had to be explored in the very early studies of agricultural machine vision. Several authors including Guyer *et al.* (1986) and Reid and Searcy (1988) described implications due to environmental factors or technical issues (e.g. lack of robustness) in their studies. Guyer *et al.* (1986) also concluded that for mechanical weed control systems, it would suffice to differentiate between crop and no crop (weeds) only. This was an important statement since it already suggested to keep the technology as simple as possible and that the focus of machine guidance should rest on recognizing the most prominent structure inside a field: the crop rows. By combining machine vision with radio navigation, the precision of the weeding operation can be increased further (Tillett, 1991). It was also observed that major issues arose from mounting a camera system in the front of the tractor because the distance to the cultivator in the rear was too far and complicated the implement guidance (Billingsley and Schoenfisch, 1995, 1997). The risk for alignment errors increases with the distance between the camera and the cultivator.

Another issue for machine vision in an open field is lighting and the visual appearance of the crop or weed plants. This can be a variation in color between different crops or between the same crop type (e.g. red and green cabbage). The software algorithm should also be able to distinguish between different shades of the same color (e.g. green) to fine-tune the crop recognition result (Gerrish *et al.*, 1997). Shadow casting behind the